# Operationalizing Basic Research and Scholarship by the Office of Naval Research: A System-of-Systems Approach for the Military Acquisition and Application of Knowledge

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This essay explores the process of the acquisition and application of knowledge by the Department of Defense (DoD) of the United States of America, based upon policies and practices of the Office of Naval Research (ONR). Two components are considered: "the bench" and "the brains." From a project management perspective, "the bench" is organized by the agency's strategic plans and goals, which establish scientific objectives that are realized through a roadmap provided by the Technology Readiness Level framework to address areas of inadequate coverage, or "gaps," in DoD and Department of the Navy (DoN) knowledge and expertise. "The brains" is a collective term for the participating scientists, scholars, and prototype design team in the effort. They may participate to only a limited degree, contributing narrowly within their areas of subject matter expertise. However, participation in a research program also offers opportunities to develop new directions of research and scholarship that are grounded firmly in current disciplinary rigor. In this sense, the programs contribute to development of intellectual infrastructures focused on innovation.

"System-of-Systems" approaches have developed since the mid-

*boundary 2* 44:4 (2017) DOI 10.1215/01903659-4206277 

twentieth century as a formal approach for the analysis and design of systems that are composed of independent subsystems working toward a common goal (Nielsen et al. 2015; Walden and Roedler 2015). The evolving discipline of System-of-Systems engineering has an impact in areas that include defense, disaster response, critical infrastructure design, logistics management, health care delivery, and computer architecture design. A research and technology portfolio is also an example of a complex system-of-systems. The individual participants and the associated stakeholders are each independent subsystems, which program managers must shape into a system-of-systems to achieve the programmatic goals.

The System-of-Systems approach is currently a characteristic feature of the US Department of Defense strategy for acquisition of knowledge and translation into technology (Committee on Pre-Milestone A Systems Engineering 2008: 1–25, Office of the Deputy Under Secretary of Defense for Acquisition and Technology 2008: 1–10, Office of the Under Secretary of Defense for Acquistion, Technology and Logistics 2015: 1–15). The US Navy's research, development, and acquisition process is a strategy to guide multiple stakeholders, manage evolving threat profiles, and develop effective technologies to address the long-term needs for operational superiority.

The Naval Science and Technology (S&T) Strategy acknowledges that a sustainable, robust, and innovative research portfolio is a critical asset for meeting operational needs (Office of Naval Research 2016b: 3–13). The ONR S&T strategy process begins with an updated assessment of: (1) current Navy core capabilities, (2) projected needs of stakeholders and the Fleet/Force, and (3) global technologies and threat awareness. The investment portfolio is then adjusted to support the efforts of scientists and scholars in fundamental research that is essential for meeting short-, intermediate-, and long-term goals for naval operational systems. The strategic fundamental research agenda is focused on a five- to twenty-year horizon to address anticipated needs and technical challenges. Translation into operational applications proceeds on a shorter timeframe to produce specific S&T products.

## Technology Readiness Levels: Defined Roles for Different Knowledge Development Stakeholders

The Technology Readiness Level (TRL) framework provides a systematic approach for knowledge development and operational implementation. This approach recognizes the pivotal but distinct roles of fundamental researchers and scholars, the private sector, and military stakeholders in different stages and facets of the research, development, system validation and evaluation cycle, and eventual transition to operational use. The preservation of an independent role of basic, fundamental research and scholarship is a hallmark of the TRL framework. One measure of the success of this approach is the history of ONR support for fundamental research of almost sixty Nobel Laureates, including thirty-seven laureates since 1980 (Office of Naval Research 2016a). This continuing record of vigorous and productive support for innovative and fundamental research is an underappreciated product of processes for the "Militarization of Knowledge."

The TRL schema is an approach for deliberate management of knowledge acquisition and translational strategies to produce deliverables that protect and support personnel (Assistant Secretary of Defense for Research and Engineering 2011: 2-13–14). The TRL structure organizes the effort and roles of different participants from the academic sector, the private sector, and the government sector from the formative concept stage through postdeployment evaluation and improvement. The levels are hierarchical, with recognition of specific roles for fundamental research by investigators who have no potential conflicts of interest or conflicts of commitment with later product development. The TRL framework is shared by other agencies, including the Department of Energy (US Department of Energy 2011: 1–12), National Aeronautics and Space Administration (National Aeronautics and Space Administration 2016), and the Department of Health and Human Services (Department of Health and Human Services, US Public Health Service 2016).

The TRL framework has three general maturity stages that engage different stakeholders. The first stage, TRL 1 to TRL 4, engages normal university faculty research and development (R&D) roles and processes. Project development proceeds from reporting basic observations and principles (TRL 1) through prototype construction and validation in a laboratory setting (TRL 4). The exploratory and hypothesis-driven basic and applied research projects are similar in scope to investigator-initiated grants from other agencies and sources. Basic research components may address a fundamental, abstract issue; applied research components generally address concrete problems related directly to technology development.

The second maturity stage, TRL 5 to TRL 8, marks the transition from science-based prototypes to operational technologies and products. The Navy, as a customer, works primarily with industrial partners through the processes of successively more comprehensive prototype assembly, demonstrations, and extensive lab testing. The maturation of the technology is validated in TRL 7 and TRL 8, with extensive testing in operational environments and qualification of the products for deployment in final form. This process is effectively a process of commercialization in partnership with industry. The final stage, TRL 9, is performance monitoring in regular Operational Test and Evaluation (OT&E) reports.

The transition from basic and applied research to technology transfer and product development requires an orderly transfer of responsibilities from fundamental and applied R&D partners to industry partners. Universities and other nonprofit institutions contribute expertise in developing fundamental and early-stage applied knowledge, while corporate sector partners contribute demonstrated capabilities to develop, manufacture, and support new products. An orderly transition of effort guides budget allocations to different partners and stakeholders during TRL 1 to TRL 3 activities. For example, the ONR budget allocations for TRL 1 to TRL 3 support this transition of primary effort from the academic sector to industry. During TRL 1, approximately 60 percent of expenditures are allocated to universities and nonprofits, 30 percent to Navy research facilities, and 10 percent to industry. This pattern shifts in TRL 2 to a 45 percent allocation to industry, 30 percent to Navy research facilities, and 25 percent to the university and nonprofit sector. It is adjusted further in TRL 3 to a 65 percent allocation to industry, 20 percent allocation to Navy research facilities, and a 15 percent allocation to the university and nonprofit sector. It is similar to a relay race, with the R&D baton passed from the research team to the industry-based system integration and product development team by the end of TRL 4. One by-product is that the TRL 4 to TRL 5 junction creates a soft firewall against the contamination of subsequent testing and evaluation of commercial products by potential conflicts of interest (or commitment) from owners and assignees of fungible intellectual property underlying the technology.

Progress is defined in the TRL framework by knowledge acquisition milestones or goals in different R&D focus areas. As a result, it is natural for the TRL to be applied to managing portfolios of highly interdisciplinary focus areas with multiple goals and timescales for completion. Let us consider two examples of objectives within focus areas of the current US Naval Science and Technology Strategy. Firstly, "Human/Unmanned Systems Collaboration" is one of five objectives within the US Navy focus area of "Autonomy and Unmanned Systems." This objective includes developing natural modes of communication between humans and machines, understanding intent and recognizing deception, and developing approaches for dynamically altering levels of autonomy that are distributed across participants in a human-machine system. Secondly, "Warfighter Health and Survivability" is one of four objectives in the "Warfighter Performance" focus area. This objective spans acute and chronic health issues, ranging from improving the continuum of combat casualty care (point of injury to specialized treatment facility) to reducing the incidence of noise-induced hearing loss in operational environments. These objectives encompass multiple research programs that include research across disciplines and address needs that range from immediate to decades into the future.

The ONR S&T investment portfolio is divided into components that permit the R&D process to proceed on four different development horizons. The "Discovery and Invention" portfolio component supports research efforts over a relatively long, five- to twenty-year time span, anchored by basic TRL 1 and early applied TRL 2 research. The goal of this component is development of new knowledge, "the seed corn that explores nascent technologies for future application" (Office of Naval Research 2016b: 18). It accounts for approximately 45 percent of the budget of ONR and supports fundamental research efforts. If one considers the delivered applied products as analogous to the fruit of a tree, this fundamental research agenda generates a knowledge root bed to sustain new applied efforts. The Leap-Ahead Innovations component supports higher risk TRL 2 and TRL 3 research work that will lead to innovative prototypes on a four- to eight-year horizon, with an investment of approximately 12 percent of the budget. The Technology Maturation component (later TRL 2 and TRL 3 research) adapts technologies into deliverables on a two- to four-year horizon, accounting for approximately 30 percent of the budget. Finally, Quick Reaction and Other S&T needs are addressed by TRL 3 work on a one- to two-year time line; this program accounts for approximately 8 percent of the budget.

## Academic Knowledge Generation in the TRL Framework

The progression through the TRL framework from level 1 to level 4 recognizes the specific role of basic researchers in generating knowledge that has general applicability to other domains, guided by the need to focus the findings on specific applications of interest. The first level of technology readiness, TRL 1, initiates the applied R&D process by establishing the link between fundamental principles (or findings) and applications. Deliverables from TRL 1 often include publications establishing basic principles from research activities as underpinnings for further technology development. In military medicine, TRL 1 activities include reviewing nascent technical developments and research outcomes for targets of opportunity for further work. In the technical arena, it may produce prospectus-type concept papers, or “white papers,” that describe specifications, characteristics, and behaviors for proposed systems and architectures.

The formal development of the technology concept or application begins in TRL 2. This phase involves “brainstorming” to encourage innovation and creativity within the realm of what is possible. The TRL 2 products are often speculative, without detailed analysis to support the underlying assumptions or detailed proof-of-concept work. In the military biomedical arena, they may simply be research ideas (or schemata) and protocols (US Army Medical Research and Materiel Command 2016), akin to a grant proposal to agencies such as the National Science Foundation (NSF) or the National Institutes of Health (NIH).

Applied research work is the domain of TRL 3. Scholarship, analytical studies and laboratory studies are conducted to validate assumptions and analytical predictions that were developed during TRL 2. In the military biomedical arena, proof-of-concept experiments are often conducted in vitro and in vivo to confirm key predictions of hypotheses formulated in TRL 1 to 2 work. Clinical research could include drug trials at TRL 3.

The first demonstration prototypes for a technological product are assembled and tested in a laboratory (or other contextually sparse) environment during TRL 4. For complex systems, the specifications and capabilities of individual components and/or combinations of components are validated in a laboratory environment. The goal is to benchmark the ability to achieve system concepts on the basis of the work completed in TRL 3, by determining how the performance of “bare bones” prototypes differs from the expected system performance that was envisioned in TRL 2. For example, an image-processing architecture for target recognition and tracking would be validated by its ability to detect artificial, small, noisy targets in a large, noisy environment. Medical devices, pharmaceutical drugs, and pharmaceutical biologics would be validated by preclinical proof of concept studies in laboratory or animal models at TRL 4.

For most technologies, the prototype and component validation in a relevant operating environment of TRL 5 marks the transition to primary industry participation. However, academic medical centers have an extended role in TRL 5 to TRL 8 programs for medical device and pharmaceutical development. Because these products must comply with regulations in the jurisdiction of the Food and Drug Administration (FDA), these TRLs in the biomedical area are mapped directly onto milestones established for the FDA approval process. Preclinical studies in TRL 5 support applications for Investigational New Drug (IND) approval or review of Investigational Device Exemption (IDE) results. During TRL 6, Phase 1 studies are conducted, and IND applications are reviewed by the FDA. During TRL 7, Phase 2 trials are conducted, and Phase 3 plans are submitted for FDA review. Phase 3 studies are conducted during TRL 8. The roles of clinical faculty and academic medical centers are indistinguishable from their civilian sector counterparts.

From the perspective of a scholar or a scientific researcher in an academic setting, participation in these research programs is very similar in scope to participation in projects funded by investigator-initiated grants or multi-investigator projects from agencies such as the NIH or NSF. Participation in TRL 1 to TRL 3 research involves the completion of circumscribed exploratory and hypothesis-driven projects. The research work is "business as usual," the completion of fundamental, basic, and applied research projects, followed by dissemination of the findings at scientific conferences, in reports to the sponsor, and in peer-reviewed publications for the community at large. In essence, a hallmark of the framework is a major role for the normative culture of open academic discourse and the fundamental research mission of universities.

### Building Intellectual Infrastructure for Innovation: The Brains

Because the ONR research focus areas transcend current disciplinary boundaries, program managers face the challenge of developing a portfolio of research teams that works effectively across those boundaries to meet deadlines for knowledge acquisition milestones or goals. Hence, the research portfolios mirror the highly interdisciplinary focus areas, and the management requires agility in setting multiple goals and timescales for coordinated completion of the program.

The ONR R&D focus areas are motivated by anticipated operational needs for Navy and Marine Corps activities. The current and future needs for knowledge acquisition and operational application span the humanities and sciences. The current portfolio includes nine areas: (1) Assured Access to Maritime Battlespace, (2) Autonomy and Unmanned Systems, (3) Electromagnetic Maneuver Warfare, (4) Expeditionary and Irregular Warfare, (5) Information Dominance—Cyber, (6) Platform Design and

Survivability, (7) Power and Energy, (8) [Force] Power Projection and Integrated Defense, and (9) Warfighter Performance. Each focus area incorporates "big idea," multiple research issues that require multidisciplinary solutions. For example, the Expeditionary and Irregular Warfare Focus Area includes an objective of improving irregular warfare operations capabilities by incorporating (1) social, cultural, and behavioral domain understanding, model, and analysis, (2) tactical cyber operations with delimited effects, and (3) social media exploitation and management. The Autonomy and Unmanned Systems Focus Area includes goals of: (1) developing natural modes of communication between humans and machines, (2) understanding intent and recognizing deception, and (3) developing approaches for dynamically altering levels of autonomy that are distributed across participants in a human-machine system. The Warfighter Health and Survivability component of the Warfighter Performance Focus Area is also multifocal, with programs to: (1) improve the continuum of casualty care from point of injury to definitive care in treatment facilities, (2) influence development of advanced materials and design for body armor and equipment, (3) improve health and performance in undersea operations, (4) enhance resilience to physical and psychological stressors, and (5) reduce the incidence of noise-induced hearing loss and explore mitigation and remediation.

Each of the components of a focus area requires the assembly and management of a multidisciplinary portfolio of investigators with integrative expertise to meet programmatic goals. The ONR Noise-Induced Hearing Loss Program provides an example of implementation of the strategy. This program addresses a major occupational hazard that affects operational capabilities and quality of life for active personnel, veterans, and their families. Noisy military operational environments contribute to a high prevalence of progressive sensorineural hearing loss (Groenewold et al. 2010). The TRL 1 to 3 broad scientific objectives are directed simultaneously at mitigation of two interacting systems, a noisy physical environment (e.g., flight deck of an aircraft carrier) and susceptible human personnel, including both barrier (e.g., personal protective equipment) and biological monitoring and countermeasures. Hence, the program is driven to generate a solution space that integrates a combination of engineering controls and biological countermeasures.

Four areas, or thrusts, are addressed. A research agenda that targets source noise reduction includes assessment of shipboard noise levels and the identification and validation of paths for shipboard noise propagation. These findings can be applied directly to the development of engineering controls, which may include installation of new noise mitigation systems and design changes for future vessels. Because jet aircraft are a major noise source on aircraft carriers, the program also supports engineering research for jet engine noise reduction. The research thrust in the areas of incidence, susceptibility, and evaluation of hearing loss includes development (and validation) of new assessment tools for functional hearing. A new virtual hearing loss simulator has also been developed for inclusion in education programs that seek to increase voluntary compliance with wearing hearing protection. The Medical Prevention and Treatment research thrust supports fundamental research into the sequelae of noise and blast wave exposure to the auditory system, which includes work in neurobiology, regenerative medicine, pharmacology, and drug delivery vectors. The fourth thrust area is in development and fielding of improved Personal Protective Equipment (PPE) for personnel operating in noisy environments while maintaining situational awareness and communication capabilities. A device has been developed for rapid three-dimensional digitization of the external ear canal for manufacturing custom-fitting ear plugs. Devices are also under continuous development of in-ear sound dosimetry, dive helmet underwater noise control, and shipboard PPE.

The management strategy for these programs includes periodic program review or “State of the Science” meetings to evaluate progress in focus areas and build an investigative community that generates basic knowledge to address future needs. All investigators receive a comprehensive overview about progress toward program goals, which establishes a common picture and engages the management team and investigators (the brains) as the intellectual infrastructure for the effort. These meetings are a programmatic component to build a vibrant and self-sustaining basic research community in areas of strategic need. The goal is to leverage the natural synergy between products of the fundamental research missions of participants and institutions, emerging challenges to national well-being, and innovation to mitigate those challenges.

## Conclusion and Modified Metaphor: ONR S&T System-of-Systems as an Orchard

The characterization of the ONR S&T Discovery and Invention portfolio as the seed corn for nascent technology development seems to be an understatement. Rather, the ONR S&T strategy can be viewed metaphorically as an orchard. The broadly focused, long-term commitment to fundamental research in the Discovery and Invention portfolio may be more aptly characterized as the root network and root stock of the orchard, anchored by the participants and the TRL 1 to TRL 2 scientific findings and publications. The success of the strategy is grounded in the ONR's portfolio of fundamental research in chemistry, physics, economics, and medicine (life sciences), which includes engagement of an impressive cadre of Nobel Laureates. By design, this longer-term effort is managed (tended and pruned) on a horizon of five to twenty years, and the budget is allocated preferentially to support fundamental research in the academic sector. Hence, there is implicit recognition that basic researchers and their institutions excel in knowledge generation at TRL 1 and TRL 2. Significantly, the strategy does not dilute their efforts into the entrepreneurial, product delivery domain.

Narrowly focused applications emerge as the "branches" during TRL 3 and TRL 4 stages of development. Mature, "fruit-bearing branches" are TRL 5 to TRL 8 translations of knowledge and know-how into applications and products. These applications of knowledge address a broad range of Navy operational needs to meet present and nascent challenges. The practical impact of ONR-supported fundamental research extends to areas that include management practices, human factors engineering, cybernetics, advanced material design, medical care, computer science, sensor technologies, spectroscopy, precision timekeeping, secure communications, fuel production, decision support systems, and biometrics. Prototype and product development are the primary domain of sectors that manufacture, evaluate, and service deliverable products.

Individual ONR focus areas each provide examples of how the Naval Science and Technology Strategy tailors programs for knowledge acquisition that both meet emergent challenges and anticipate solutions to future threats. The TRL framework for development respects the fundamental research agenda of academic investigators and institutions and prevents potential conflict of interest issues by a transition to product development and evaluation by the corporate sector. It has proven to be a sustainable process for fostering scientific advances and selective production of state-of-the-art deliverables that support military operational needs, often with collateral benefits to our citizenry as a whole.

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